

THE REFINED SHOCK VELOCITY OF THE X-RAY FILAMENTS IN THE RCW 86 NORTHEAST RIM

HIROYA YAMAGUCHI^{1,2}, SATORU KATSUDA³, DANIEL CASTRO¹, BRIAN J. WILLIAMS¹,
LAURA A. LOPEZ⁴, PATRICK O. SLANE⁵, RANDALL K. SMITH⁵, ROBERT PETRE¹*Draft version March 1, 2016*

ABSTRACT

A precise measurement of shock velocities is crucial for constraining the mechanism and efficiency of cosmic-ray (CR) acceleration at supernova remnant (SNR) shock fronts. The northeastern rim of the SNR RCW 86 is thought to be a particularly efficient CR acceleration site, owing to the recent result in which an extremely high shock velocity of $\sim 6000 \text{ km s}^{-1}$ was claimed (Helder et al. 2009). Here we revisit the same SNR rim with the *Chandra* X-ray Observatory, 11 years after the first observation. This longer baseline than previously available allows us to determine a more accurate proper motion of the nonthermal X-ray filament, revealing a much lower velocity of $3000 \pm 340 \text{ km s}^{-1}$ (and even slower at a brighter region). Although the value has dropped to a half of that from the previous X-ray measurement, it is still higher than the mean velocity of the H α filaments in this region ($\sim 1200 \text{ km s}^{-1}$). This discrepancy implies that the filaments bright in nonthermal X-rays and H α emission trace different velocity components, and thus a CR pressure constrained by combining the X-ray kinematics and the H α spectroscopy can easily be overestimated. We also measure the proper motion of the thermal X-ray filament immediately to the south of the nonthermal one. The inferred velocity ($720 \pm 360 \text{ km s}^{-1}$) is significantly lower than that of the nonthermal filament, suggesting the presence of denser ambient material, possibly a wall formed by a wind from the progenitor, which has drastically slowed down the shock.

Subject headings: acceleration of particles — ISM: individual objects (RCW 86) — ISM: supernova remnants — proper motions — shock waves — X-rays: ISM

1. INTRODUCTION

It is widely believed that supernova remnants (SNRs) are the predominant source of Galactic cosmic-rays (CRs) with energies up to $\sim 3 \text{ PeV}$ (e.g., Reynolds 2008). RCW 86, probably the remnant of SN 185 (e.g., Clark & Stephenson 1975; Vink et al. 2006), is thought to be an efficient CR accelerator, based on the detection of nonthermal X-rays (Bamba et al. 2000; Borkowski et al. 2001; Rho et al. 2002) and γ -rays (Aharonian et al. 2009; Yuan et al. 2014). The large amount ($\sim 1 M_{\odot}$) of Fe ejecta in a low ionization state (Yamaguchi et al. 2011, 2014) and Balmer-dominated shocks (Smith 1997) observed in RCW 86 suggest a Type Ia supernova origin. The remnant is likely to have evolved in a wind-blown cavity formed by the progenitor binary system (Williams et al. 2011), maintaining a high enough shock velocity to accelerate CR particles over the entire lifetime of the remnant. In particular, its northeast (NE) rim is still expanding within the low-density cavity or has encountered the cavity wall very recently, so its current shock speed is the highest within the entire remnant (Vink et al. 1997; Yamaguchi et al. 2008; Broersen et al. 2014). For this reason, the NE rim

of RCW 86 has been frequently studied to understand the details of the CR acceleration mechanism.

A velocity of the SNR shock wave in combination with the physical condition of the postshock plasma offers a key for constraining the CR acceleration efficiency. The most direct way to determine the shock velocity is to measure the proper motion of the shock front. Using two *Chandra* observations of the RCW 86 NE rim taken in 2004 and 2007, Helder et al. (2009) (hereafter H09) obtained the proper motion of the nonthermal X-ray filaments over a three-year baseline to be $1''.5 \pm 0''.5$. This proper motion corresponds to a shock velocity of $6000 \pm 2000 \text{ km s}^{-1}$ at the well-agreed distance of 2.5 kpc (Rosado et al. 1996; Sollerman et al. 2003). H09 also analyzed an H α spectrum from the same region and derived a postshock proton temperature of $2.3 \pm 0.3 \text{ keV}$ based on the width of the emission lines. This was unexpected because the theoretical relationship between the postshock temperature and shock velocity, $kT = (3/16)\mu m_p V_s^2$ (where μ and m_p are the mean particle mass and the proton mass), predicts a much higher postshock temperature ($kT = 42\text{--}70 \text{ keV}$ depending on the degree of thermal equilibration) for $V_s = 6000 \text{ km s}^{-1}$. H09 attributed this discrepancy to the efficiency of the CR acceleration: a substantial fraction of the kinetic energy is being transferred into nonthermal energy. They concluded that $>50\%$ of the postshock pressure is produced by the CR protons.

In their follow-up H α observation, however, the mean proper motion of the forward shock filaments was inferred to be $0''.10 \pm 0''.02 \text{ yr}^{-1}$, corresponding to a velocity of only $1200 \pm 200 \text{ km s}^{-1}$ (Helder et al. 2013, hereafter H13). This velocity is far lower than their previous

Electronic address: hiroya.yamaguchi@nasa.gov

¹ NASA Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA² Department of Astronomy, University of Maryland, College Park, MD 20742, USA³ Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagami-hara, Kanagawa 229-8510, Japan⁴ Department of Astronomy and Center for Cosmology & Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA⁵ Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Table 1
Summary of the Observations.

| Obs. ID | 4611 | 16952 |
|---------------------|--------------|--------------|
| Observation Date | 2004 June 15 | 2015 June 26 |
| Instrument | ACIS-S | ACIS-S |
| Pointing R.A. (deg) | 221.27 | 221.28 |
| Pointing Dec. (deg) | -62.35 | -62.35 |
| Roll Angle (deg) | 295.16 | 293.58 |
| Exposure Time (ks) | 71.7 | 67.2 |

X-ray measurement, and consistent with the measured proton temperature (~ 2 keV) with no energy injection to CR acceleration. H13 suggested that the $H\alpha$ -bright filaments are biased toward denser regions with decelerated shock velocities, while the X-ray-emitting filaments represent the relatively undecelerated regions of the shock. This scenario seems reasonable, given the fact that the forward shock of the SNR is interacting with an inhomogeneous medium (e.g., Williams et al. 2011). In fact, H13 found substantial variation in the velocity of the $H\alpha$ filaments (ranging from 300 to 3000 km s^{-1}). We note, however, that there is also a substantial uncertainty in the X-ray velocity measurement of H09, due to the small separation in time (only 3 yrs) between the two *Chandra* observations. The positional shift they obtained ($1''.5 \pm 0''.5$) corresponds to only 3 ± 1 pixels of the *Chandra*/ACIS detector. An additional X-ray observation using a much longer baseline is therefore crucial for determining the precise shock velocity.

Here we present the latest *Chandra* observation of the RCW 86 NE rim obtained in 2015, which is 11 years after the first observation. It reveals a much slower velocity of the nonthermal X-ray filaments than measured by H09. In §2, we describe the observations and data analysis. We discuss the results in §3, and present our conclusions in §4. Since the aim of the present work is to report the accurate velocity of the forward shock, we focus exclusively on the imaging analysis in this *Letter*. Detailed spectroscopy and further studies will be presented in a future paper. The uncertainties quoted in the text and the error bars in the figures represent the 1σ confidence level, unless otherwise stated.

2. OBSERVATIONS AND RESULTS

We observed the NE rim of RCW 86 on 2015 June 26 using the *Chandra*/ACIS-S chips. As summarized in Table 1, the aim point and roll angle were set almost identical to those in the first observation of this region in 2004 (Vink et al. 2006), so that we can measure the proper motion as accurately as possible. We used CIAO version 4.8 and the latest calibration database (CALDB) for the data analysis. Examination of the light curves revealed no significant background flares. The net exposure we obtained was 67 ks.

Figure 1 shows the exposure-corrected ACIS image of the 0.5–1.0 keV (red), 1.0–2.0 keV (green), and 2.0–5.0 keV (blue) bands, indicating that the dominant X-ray emission component changes from thermal (red) to non-thermal (blue) along the filaments from the south to the north. The previous work has suggested that the southern part has already encountered the dense wall of the wind-blown cavity, whereas the northern part is still in the low-density cavity and thus maintains a high CR ac-

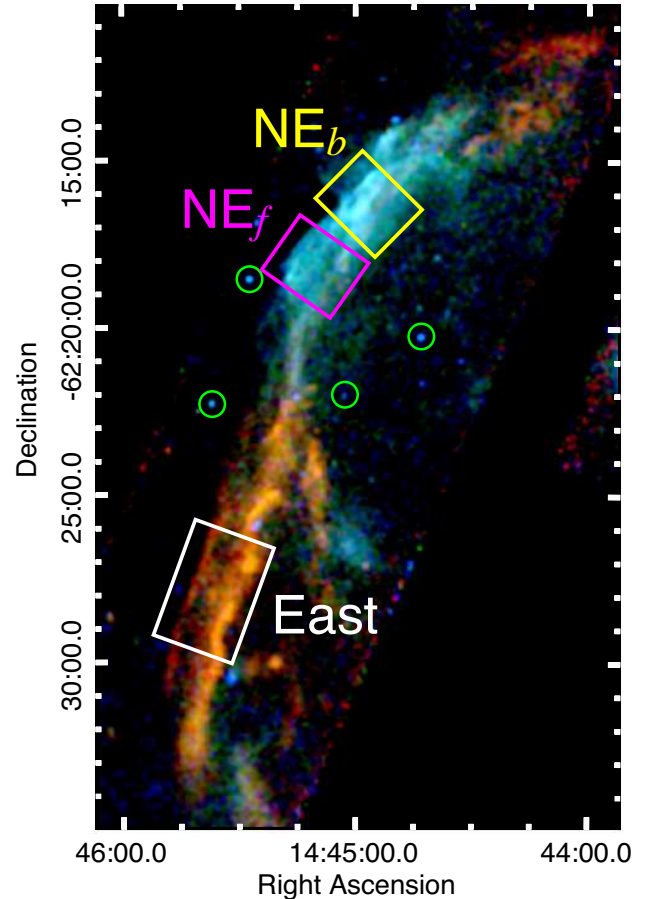


Figure 1. Three-color X-ray image of the RCW 86 NE rim obtained from the *Chandra*/ACIS-S observation in 2015. Red, green, and blue correspond to the energy bands of 0.5–1.0 keV, 1.0–2.0 keV, and 2.0–5.0 keV, respectively. The three rectangles indicate where we measured the proper motions. The background point sources indicated by the green circles are used for the coordinate realignment.

celeration efficiency (e.g., Yamaguchi et al. 2008), which we confirm below. For accurate determination of the X-ray proper motion, we compared the images from the 2004 and 2015 observations, and aligned the coordinates using the relative positions of the four background point sources indicated in Figure 1. The details of the alignment procedure are described in Katsuda et al. (2009). The RMS of the residuals for the source positions between the two epochs is only $0''.22$, which we take as a systematic uncertainty in our proper motions measurements described below.

We extract projection profiles of the nonthermal filaments from the yellow and magenta rectangles in Figure 1 (hereafter “NE_b” and “NE_f”, respectively). The latter (fainter filament) is exactly where H09 measured the shock velocity. Figure 2 (*left* and *middle*) shows the profiles from both the 2004 (black) and 2015 (red) observations, using data in the 0.5–5.0 keV band. The shock front has clearly shifted over the 11 years in both filaments. Using the method established by Katsuda et al. (2008), we determine the proper motions of the NE_b and NE_f filaments to be $0''.150 \pm 0''.020 \text{ yr}^{-1}$ and $0''.253 \pm 0''.029 \text{ yr}^{-1}$, respectively. The corresponding velocity is

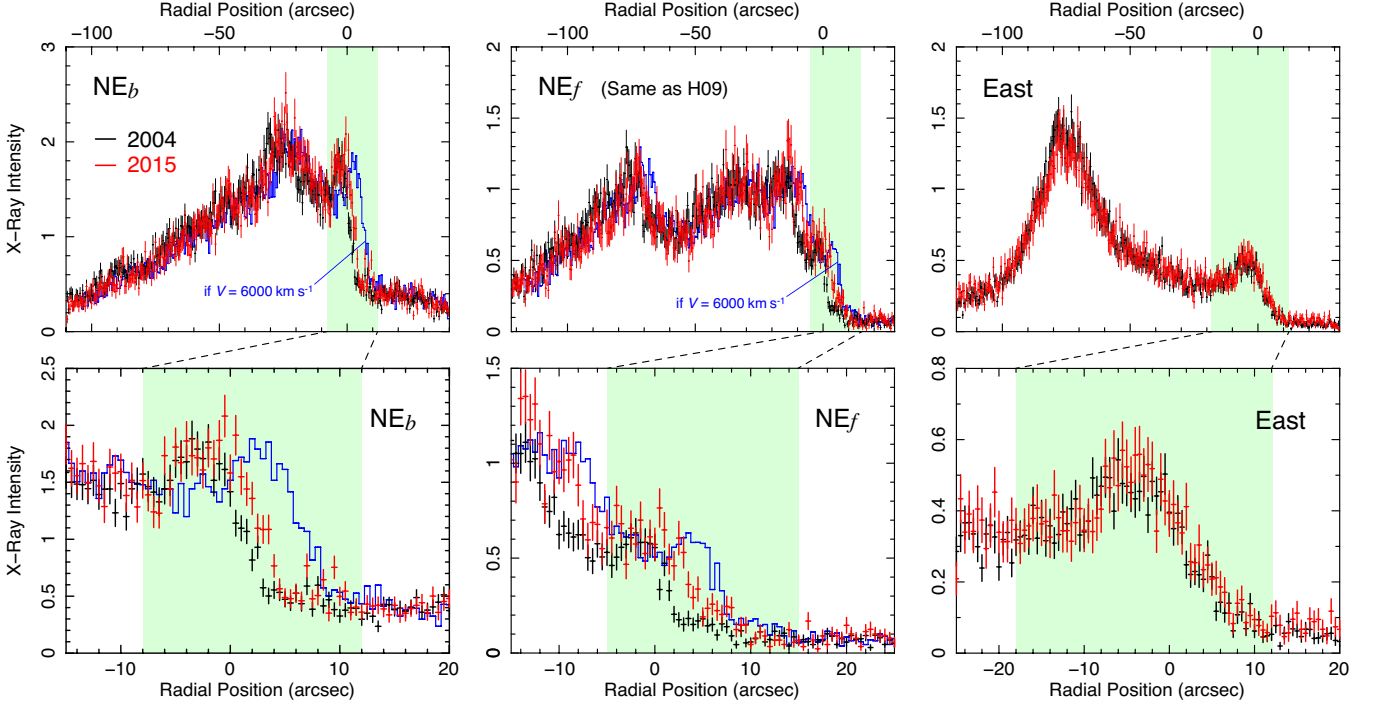


Figure 2. Projection profiles of the NE_b (left), NE_f (middle) and East (right) rims. Black and red indicate the data from the 2004 and 2015 observations, respectively. The unit of the vertical axis is 10^{-8} photons $\text{cm}^{-2} \text{s}^{-1} \text{pixel}^{-1}$. The shock front in the 2004 data is used as the origin of the horizontal axis. The bottom panels are the profiles magnifying the regions around the shock front. The data in the green regions are used to determine the proper motion of each rim. The blue lines in the left and middle panels are the profiles expected if the shock velocity is 6000 km s^{-1} as claimed by H09, which is plotted by simply shifting the 2004 profile 5.5 arcsec toward the positive direction.

$1780 \pm 240 \text{ km s}^{-1}$ for the NE_b and $3000 \pm 340 \text{ km s}^{-1}$ for the NE_f (at the distance of 2.5 kpc), significantly less than the measurement by H09. For comparison, Figure 2 (left and middle) also shows the “expected” profiles (blue solid lines) for the case of $V_s = 6000 \text{ km s}^{-1}$ (H09). An uncertainty in the distance to the SNR, $2.5 \pm 0.5 \text{ kpc}$ (Rosado et al. 1996; Sollerman et al. 2003), corresponds to that in the shock velocity of $\pm 600 \text{ km s}^{-1}$ for the NE_f filament ($\pm 20\%$ of the mean value). In addition, there is a systematic uncertainty of $\sim 260 \text{ km s}^{-1}$ inferred from the astrometric accuracy ($0''.22$ between the two epoch). We also estimate another systematic uncertainty in our measurements by slightly changing the angle of the profile extraction regions, and obtain differences only within $\pm 0''.02 \text{ yr}^{-1}$ or $\pm 240 \text{ km s}^{-1}$. To summarize, the velocity of the NE_f filament never exceeds 4500 km s^{-1} even with the multiple uncertainty components, and that of the NE_b filament must be even lower.

The large time separation between the two observations also allows us to examine if the thermal-dominated filaments have indeed decelerated due to the collision with the dense material. The right panels of Figure 2 show the profiles extracted from the white rectangle in Figure 1 (hereafter “East”). Unlike the NE filaments, we see only a little shift of the shock front. The proper motion of this region is measured to be $0''.061 \pm 0''.031 \text{ yr}^{-1}$, corresponding to $720 \pm 360 \text{ km s}^{-1}$. We establish that the East rim has a lower velocity. The value is comparable to the $H\alpha$ -measured forward shock velocity at the southwest rim of this SNR where the shock front is also interacting with dense material ($\sim 800 \text{ km s}^{-1}$: Rosado et al. 1996).

3. DISCUSSION

Our new observation of RCW 86 has revealed that the actual proper motions of the nonthermal filaments (NE_b and NE_f) are significantly slower than previously measured by H09. However, the updated shock velocities are still inconsistent with the mean velocity derived from the $H\alpha$ proper motion in this region ($\sim 1200 \text{ km s}^{-1}$: H13). This implies that the NE rim of RCW 86 has a range of shock velocities due to a small-scale density inhomogeneity, and the $H\alpha$ -bright filaments are indeed biased toward the denser regions as suggested by H13. In fact, we have revealed the significant difference between the velocities of the NE_b and NE_f filaments in our analysis. In the thermal-dominated (East) region, on the other hand, the X-ray and $H\alpha$ velocities are consistent with each other, indicating the presence of dense material with a larger spatial scale, probably a wall formed by the progenitor wind (e.g., Williams et al. 2011), that had decelerated the overall shock propagation. Assuming pressure equilibrium and thus constant $n_0 V_s^2$ along the shell (where n_0 is an ambient density), we roughly estimate the density ratio between the East and NE_f regions to be $n_{\text{East}}/n_{NE_f} \approx 17$.

Ours is not the first result casting doubt upon the extremely high velocity ($\sim 6000 \text{ km s}^{-1}$) claimed by H09. Williams et al. (2011) compared some observed characteristics of RCW 86 with their hydrodynamical simulations of a Type Ia SNR evolving in a wind-blown bubble. Although most of the characteristics were successfully reproduced with reasonable initial conditions, only the high shock velocity at the NE rim required

more complex conditions, i.e., a significant offset between the explosion center and the SNR geometrical center. Recent *Fermi* observations of RCW 86 disfavor a hadronic origin for the γ -ray emission, where the inferred CR pressure is much lower than the estimate by H09 (Lemoine-Goumard et al. 2012; Yuan et al. 2014). These discrepancies have likely been resolved by our result. Notably, the refined velocity of the nonthermal X-ray filaments ($1800\text{--}3000\text{ km s}^{-1}$) is consistent with an older estimate from the typical photon energy of the synchrotron X-rays, under the assumption that the acceleration and loss timescales for the relativistic electrons are the same (Vink et al. 2006) (see also Castro et al. (2013) for other regions of this SNR). This implies that the electrons responsible for the observed synchrotron X-rays have achieved their maximum energy at the NE region of RCW 86.

From the relationship of $kT = (3/16)\mu m_p V_s^2$, a postshock proton temperature at the NE_f region is derived to be ~ 11 keV, assuming thermal equilibrium (or higher if the equilibrium has not been achieved). Despite the substantial drop from the H09 value (i.e., $kT = 42\text{--}70$ keV), this temperature is still higher than that directly measured from the H α spectrum (~ 2.3 keV: H13). One might, therefore, consider that a significant amount of the shock energy is injected into CR acceleration. However, since the H α emission is likely to be enhanced at denser regions where the shock velocity is lower, it could be inappropriate to combine the H α and *nonthermal* X-ray measurements for studies of shock waves interacting with highly inhomogeneous environment, like the NE rim of RCW 86. We should also note that a substantial fraction of the upstream kinetic energy can be transferred into downstream turbulence, and thus the CR pressure estimated by the postshock temperature could be overestimated when naively compared with the shock velocity (Shimoda et al. 2015).

One open question is if *thermal* X-ray emission from the swept-up ambient medium coincides with the H α -bright filaments in terms of both kinematics and plasma properties. Since H α and thermal X-ray spectra constrain postshock proton and electron temperatures, respectively, they have often been combined to determine the efficiency of collisionless thermal equilibration between the protons and electrons (e.g., Rakowski et al. 2003; Helder et al. 2011). Although the proper motion measurements on the RCW 86 East (this work) as well as the northwestern rim of SN 1006 (Winkler et al. 2003; Katsuda et al. 2013) suggest a good coincidence between the thermal X-ray and H α filaments, this should be verified with additional observations of H α -bright forward shocks in other SNRs, like Kepler's SNR (Sankrit et al. 2016) and the Cygnus Loop (Medina et al. 2014). Future observations with *Hitomi* (*ASTRO-H*) will allow us to determine the ion temperature of the swept-up medium. Comparison between it and the H α -measured proton temperature will also be useful for understanding the relationship between the thermal X-ray and H α observables.

4. CONCLUSIONS

We have presented new, improved measurements of the X-ray proper motion in the RCW 86 northeastern rim using *Chandra* data taken in 2004 and 2015 (with

an 11-year separation). The velocity of the nonthermal filaments is derived to be $1800\text{--}3000\text{ km s}^{-1}$ (at the distance of 2.5 kpc), which is much lower than the previous measurement by H09, but still significantly higher than the velocity inferred from the H α proper motion (H13). This implies different origins of the filaments bright in nonthermal X-rays and H α emission, with the former having a higher velocity. Caution should be exercised before combining nonthermal X-ray kinematics and H α spectroscopy to study shock physics, at least in a complex environment such as this. We have also shown that the thermal filament immediately to the south of the nonthermal filament has a velocity of $720 \pm 360\text{ km s}^{-1}$, significantly slower than the nonthermal filament. The consistency between the velocities measured with the thermal X-ray and H α emission suggests a common origin, but this should be verified with more observational work.

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